Probing star formation in galaxies at z~1 via a radio stacking analysis

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PHISCC NCRA – TIFR February 8, 2017

Outline

- Probing Star formation with radio continuum
- Star formation rate (SFR) via stacking analysis
- Galaxy sample and selection criteria
- The GMRT images
- Stacking the radio continuum
- The star formation rate of galaxies at $z \sim 0.7 – 1.4$
- Summary

Motivation

- A number of optical deep fields (CDFS, GOODS-N, GOODS-S, COSMOS, EGS….) have yielded much information on the evolution of star formation in galaxies.
- Optical imaging and spectroscopy – positions, redshifts, stellar mass, SFR (affected by dust extinction)…
- Far infrared (FIR) or radio images are needed to determine the total SFR (unaffected by dust).
- Radio continuum too faint to detect from individual galaxies.
- "Stacking" : Statistical detection of the radio continuum.

  (e.g. Carilli et al. 2007, Pannella et al. 2009)
- Probes statistical properties of the target population.

Strategy

- Obtain the positions, redshifts and stellar mass estimates of a sample of star-forming galaxies from one of the deep surveys.
- Carry out deep 610 MHz GMRT imaging of the field.
- Stack the radio continuum at the optical positions.
- Use “median-stacking” - robust against outliers and yields a good representation of the population.

(e.g. White et al. 2007)

- Convert the measured 610 MHz flux density to the rest frame 1.4 GHz luminosity using a power law spectral index of -0.8.

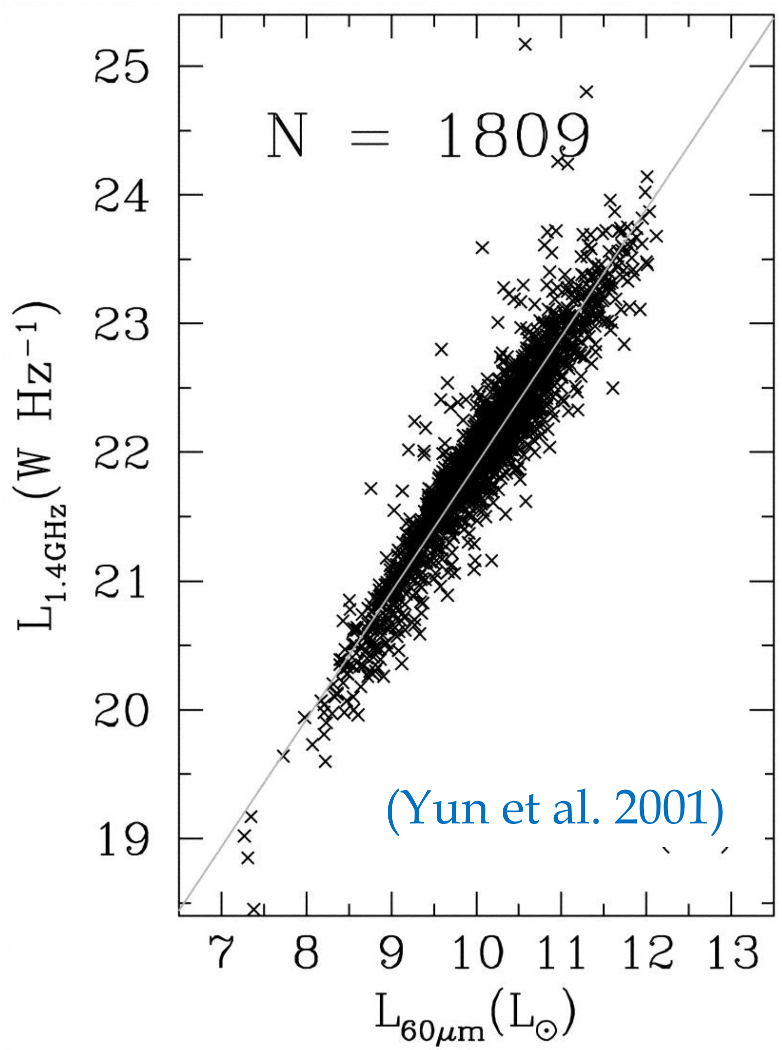
(e.g. Condon 1992)

- Estimate the median total SFR, using the radio-FIR correlation.

(e.g. Yun et al. 2001)

Total SFR from 1.4 GHz luminosity

- FIR radiation : Emission from dust heated by UV photons; Good tracer of the obscured and the total SFR.
  (e.g. Kennicutt 1998)
- In the local Universe, the rest frame 1.4 GHz luminosity is tightly correlated with the FIR luminosity.
  (e.g. Yun et al. 2001)
- FIR-radio correlation up to $z \sim 4$.
  (Pannella et al. 2015)
- Combining FIR-SFR relation and radio-FIR relation (& Salpeter IMF) :



$$\mathrm{SFR}\,(M_\odot/yr) = (5.9 \pm 1.8) \times 10^{-22} L_{1.4GHz}\,(W\ /Hz)$$

(Kennicutt 1998, Yun et al. 2001)

Our Targets: The DEEP2 Fields

- The largest magnitude-limited galaxy survey at $z \sim 1$, with accurate spectroscopic redshifts.

  (Newman et al. 2013)

- Limiting apparent magnitude $R_{AB} = 24.1$.

- Spectral range $6500 - 9100$ Å, resolution $R = 5900$ at 7800 Å.

- Redshift range $0.7 < z < 1.4$, and 38000 reliable redshifts.

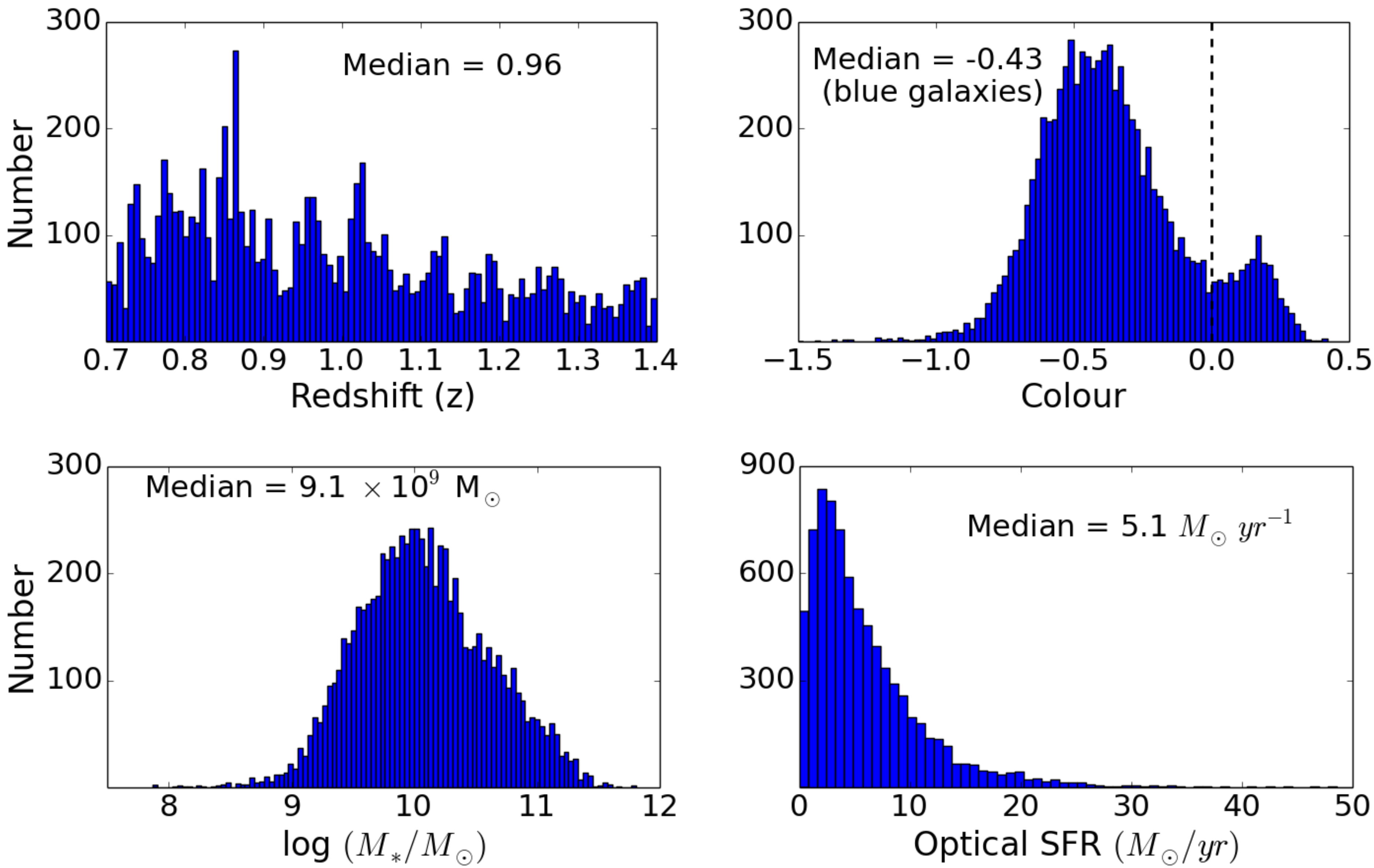
- Positions, redshifts, M_B, $(U - B)$ colour for all DEEP2 galaxies.

  (Mostek et al. 2011, Newman et al. 2013)

- The stellar mass and the optical SFR were estimated from M_B and $(U - B)$, calibrated relative to the $OII - 3727$ line SFR, for a Salpeter IMF.

  (Weiner et al. 2009, Mostek et al. 2011)

Statistics of Sources

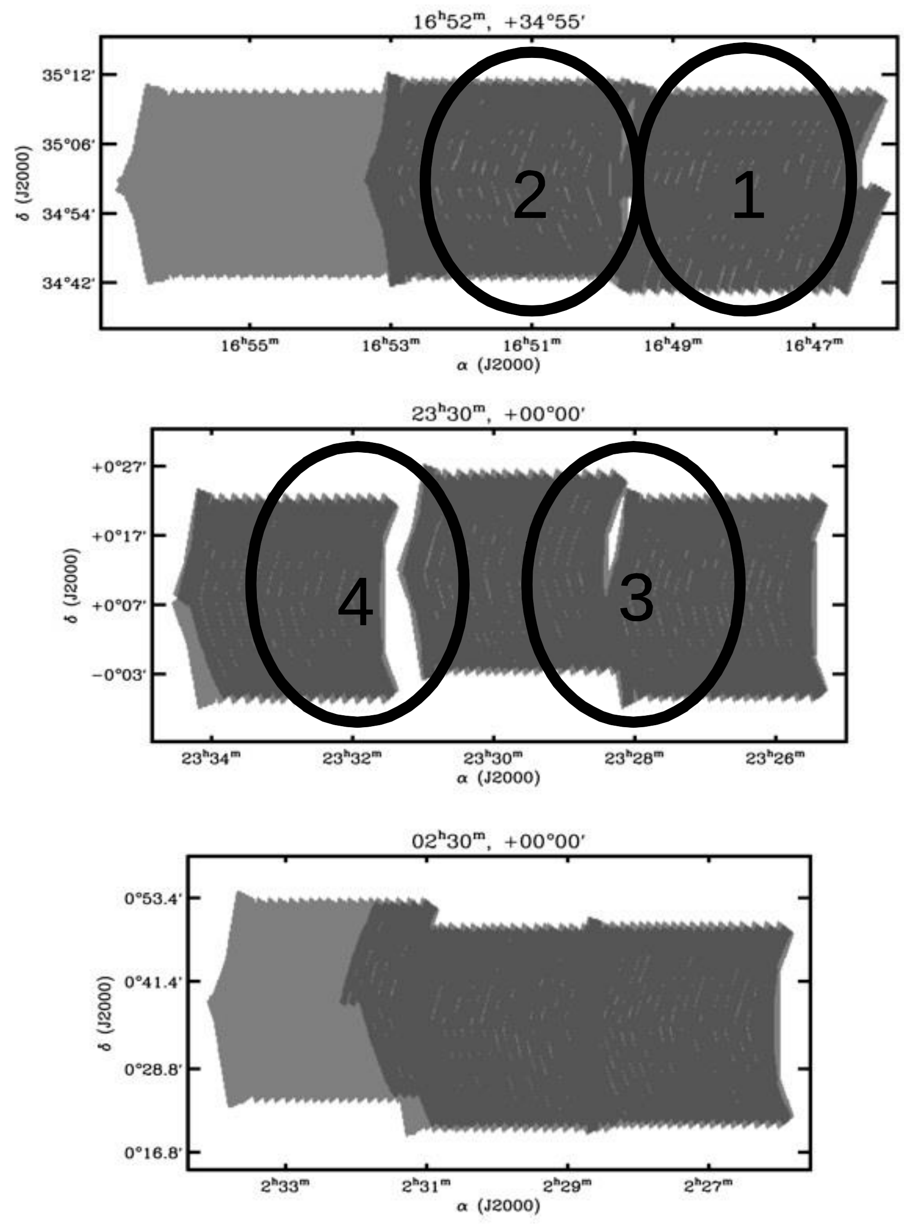


GMRT observation of DEEP2 Fields

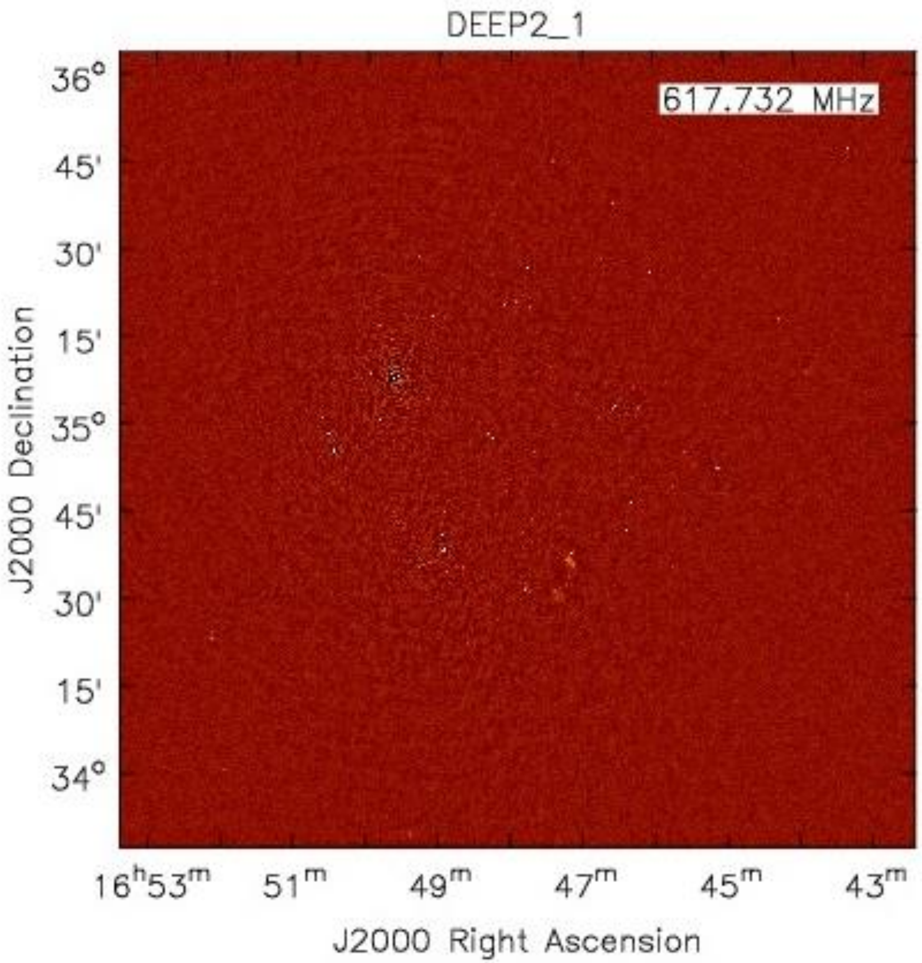
- Four DEEP2 sub-fields were observed with GMRT 610 MHz system (33 MHz bandwidth), originally for HI stacking experiment.

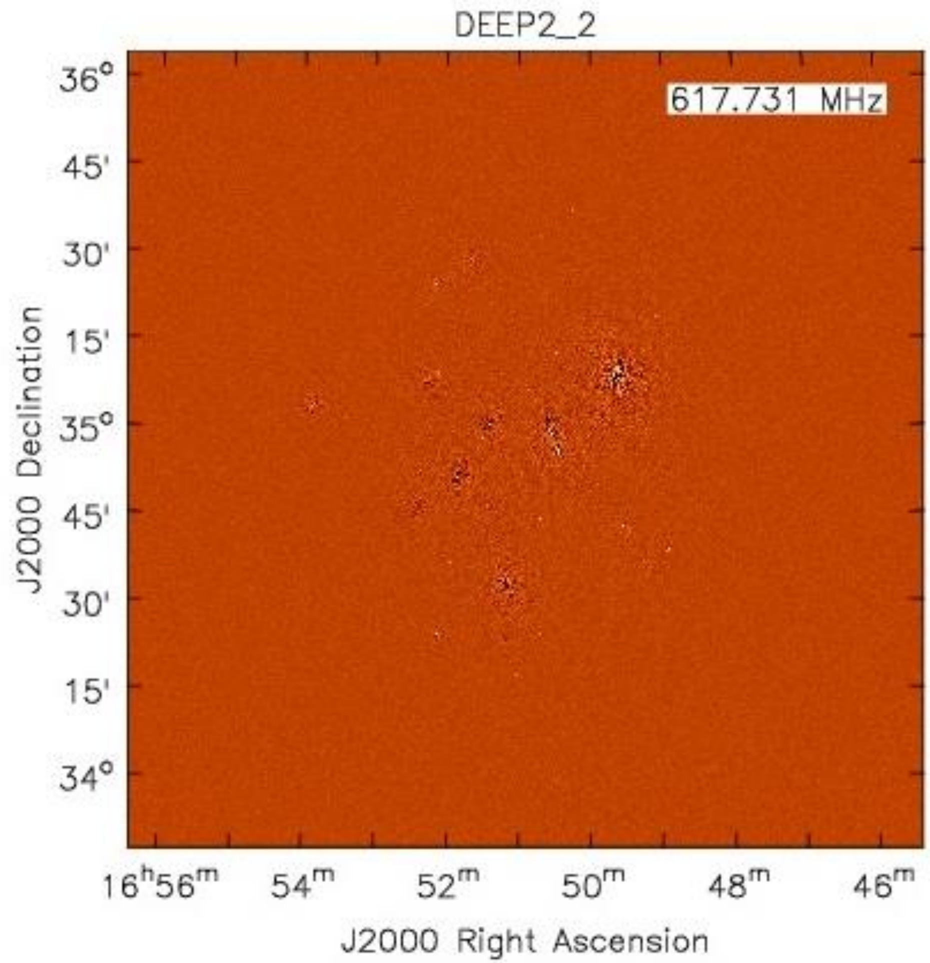
(Kanekar et al. 2016)

- 12 - 18 hours of on-source time per field.
- Calibration and self-calibration done with classic AIPS and imaging done in CASA with 1 MHz channels and 8192 × 8192 pixels.



The GMRT images

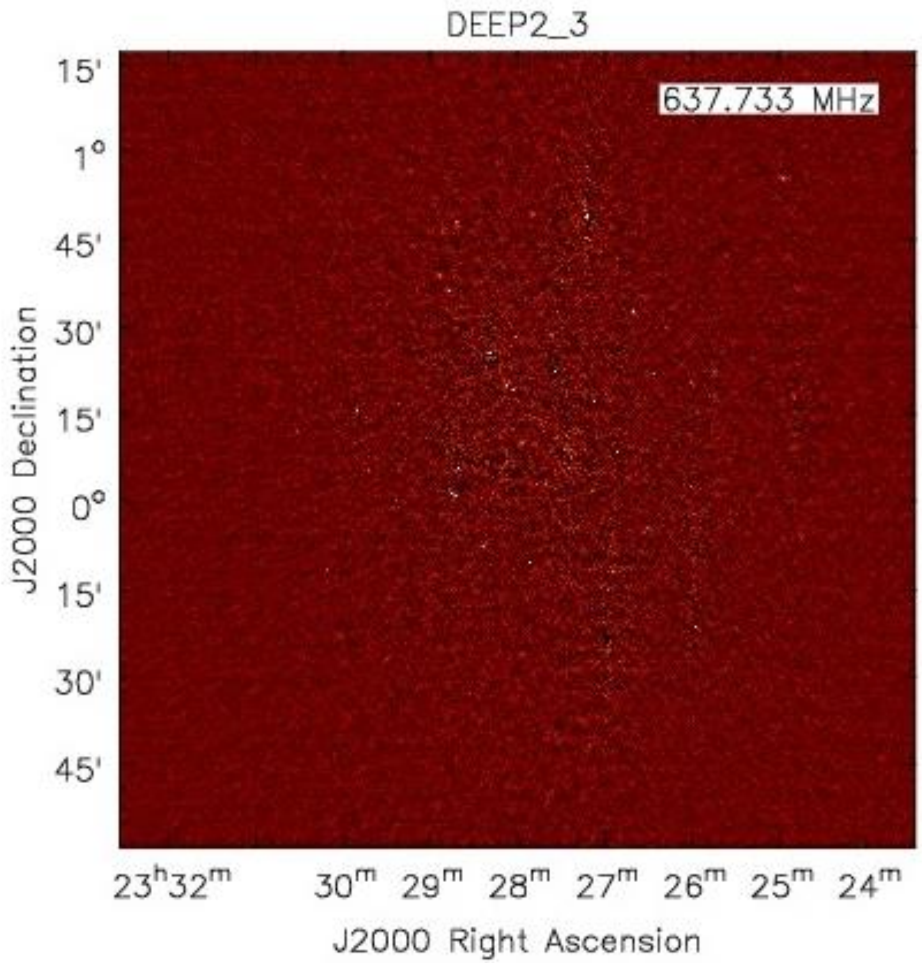


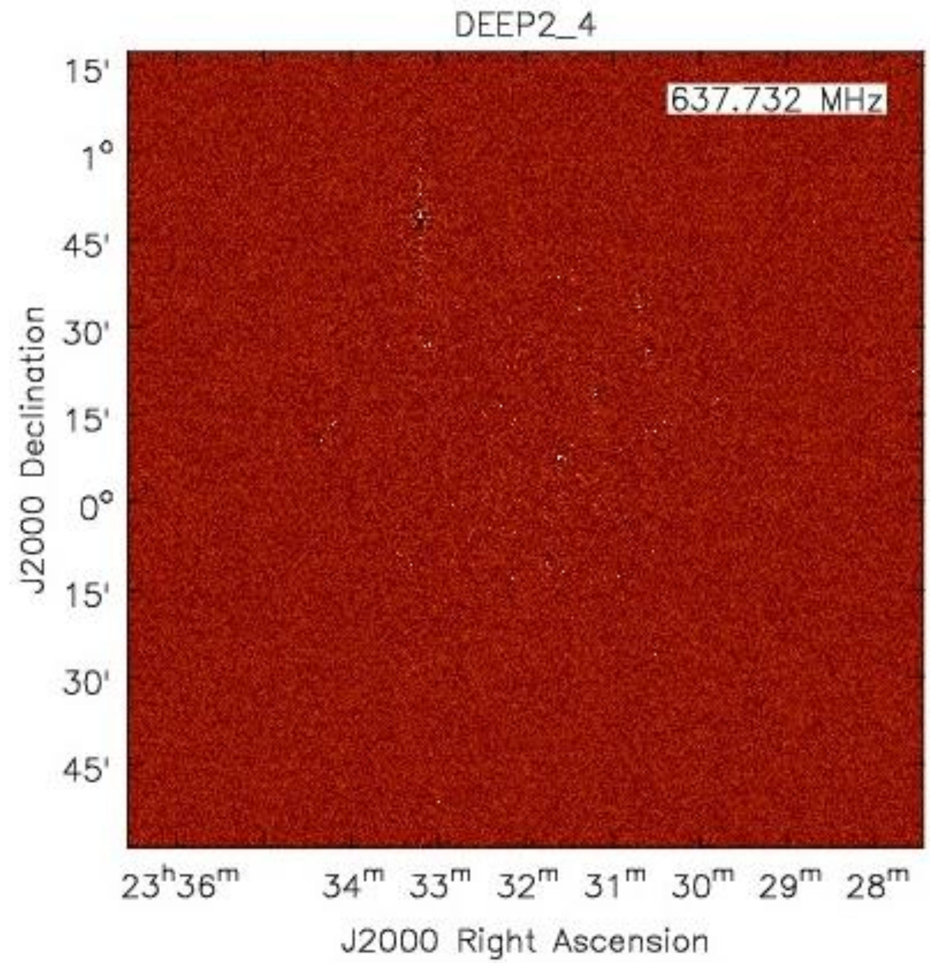


- Beam size = 4.7" × 3.9"
- RMS = 21 μJy
- 2727 DEEP2 sources (FWHM)

- Beam size = 5.2" × 4.3"
- RMS = 39 μJy
- 2979 DEEP2 sources (FWHM)

The GMRT images





- Beam size 5.9” × 4.6”
- RMS = 22 μJy
- 2325 DEEP2 sources (FWHM)

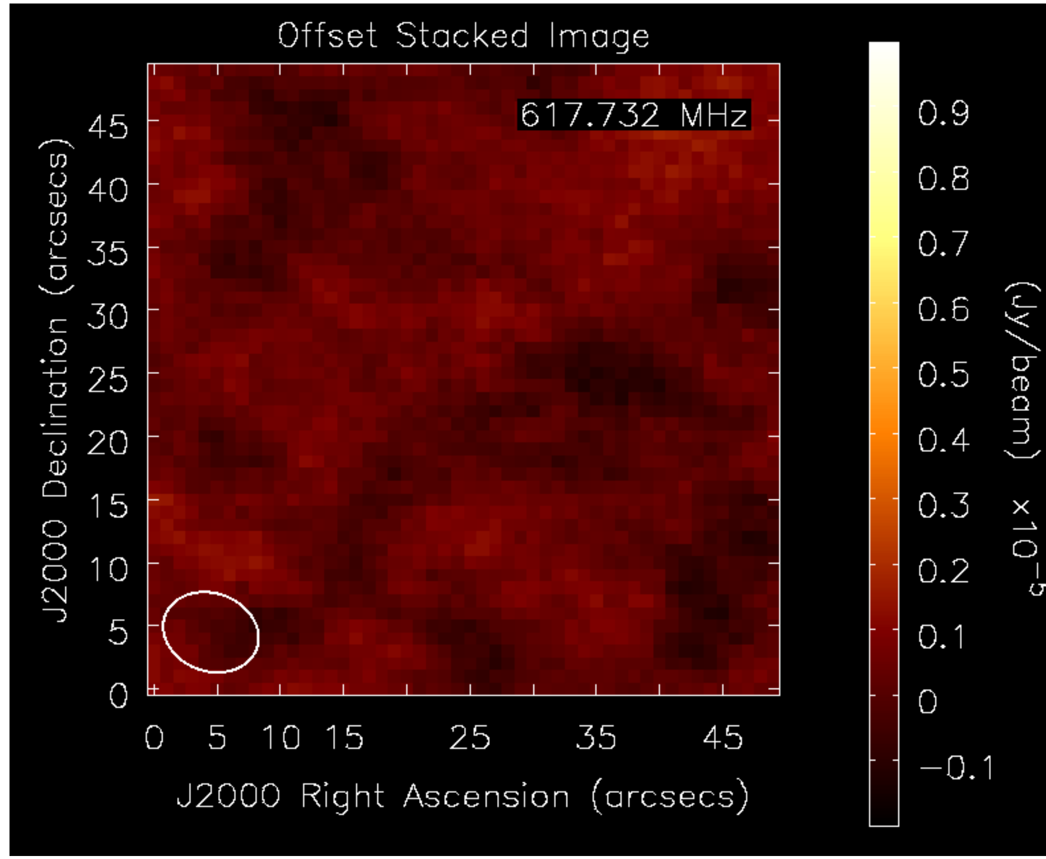
- Beam size 6.1” × 4.4”
- RMS = 14 μJy
- 2014 DEEP2 sources (FWHM)

Stacking Analysis

- Excluded galaxies outside the FWHM (43′) of the primary beam.
- Measured the local RMS noise around each DEEP2 galaxy, and excluded galaxies in the 10% tail of the RMS noise distribution.
- Excluded galaxies with pixels ≥ 5σ within 5" of the galaxy position to remove possible active galactic nuclei.
- Excluded “red’’ galaxies with “colour” > 0.
- Final number of selected galaxies in all fields – **7265.**
- GMRT images were smoothed with a common beam (6.1”×4.8”).
- Stacking done in bins of redshift, colour and stellar mass.

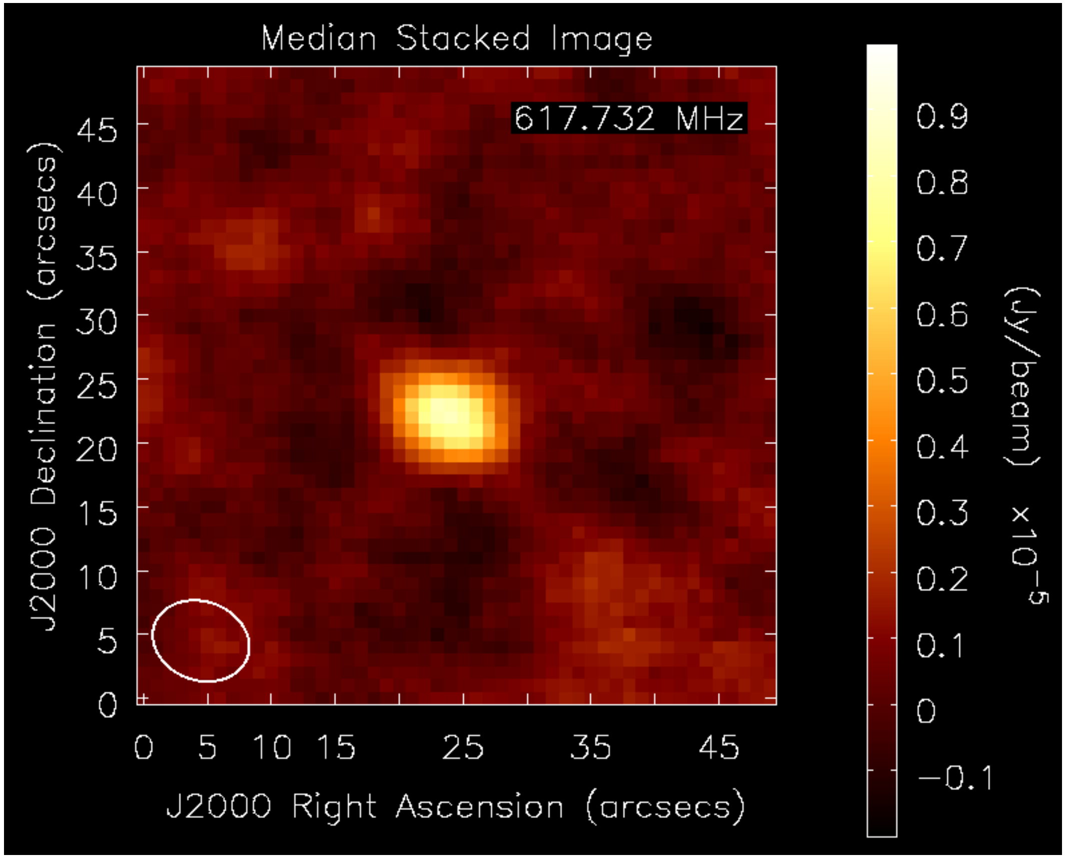
Stacking Results – Offset Locations

- Stacking of flux densities at offset locations (50 pixels away).
- Same procedure as for stacking DEEP2 galaxies.
- RMS noise = 0.53 μJy/Bm.
- No evidence for a stacked signal.



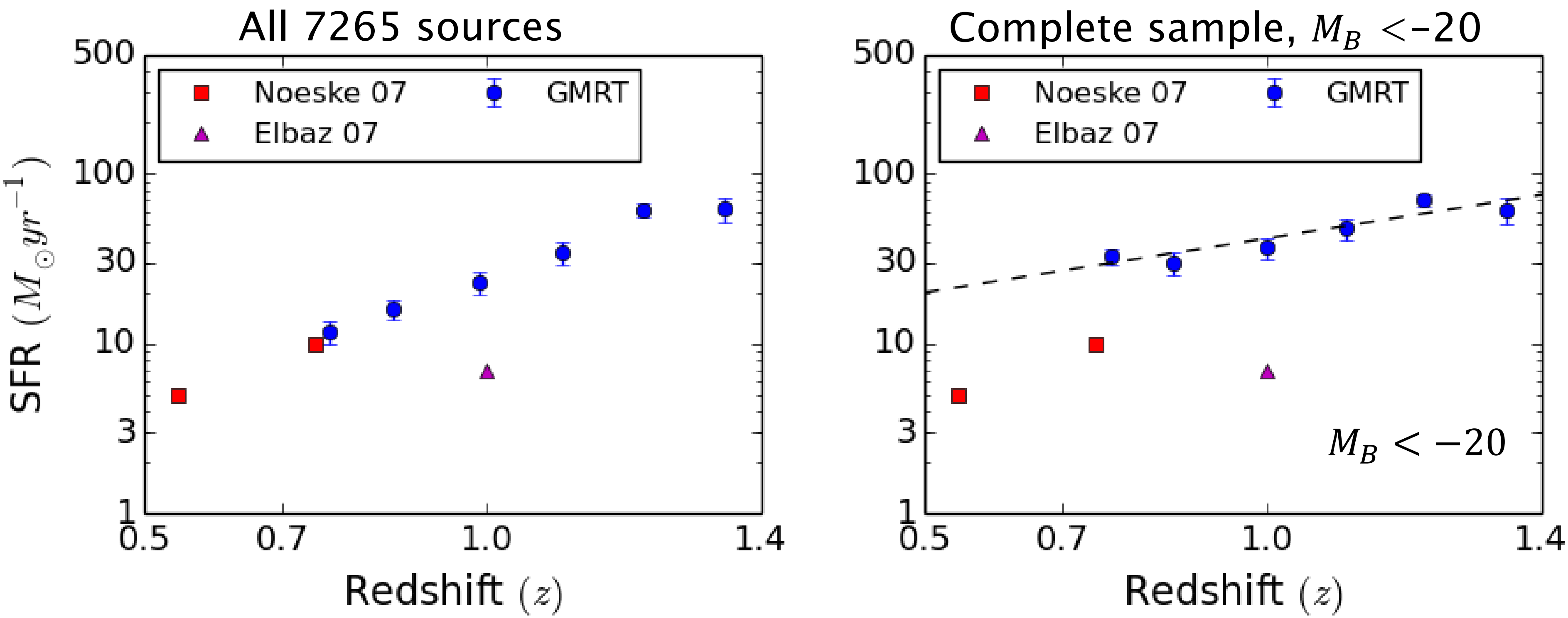
Stacking Results – All 7265 Sources

- RMS noise = 0.63 μJy/Bm.
- Source flux density = 8.42 ± 0.61 μJy/Bm (~14σ).
- Unresolved stacked emission.
- Deconvolved size: < 1.2” (< 10 kpc)
- Optical SFR: 5.1 $M_{\odot}/yr$.
- Median Radio SFR: 20.87 ± 1.53 (± 6.59) $M_{\odot}/yr$.



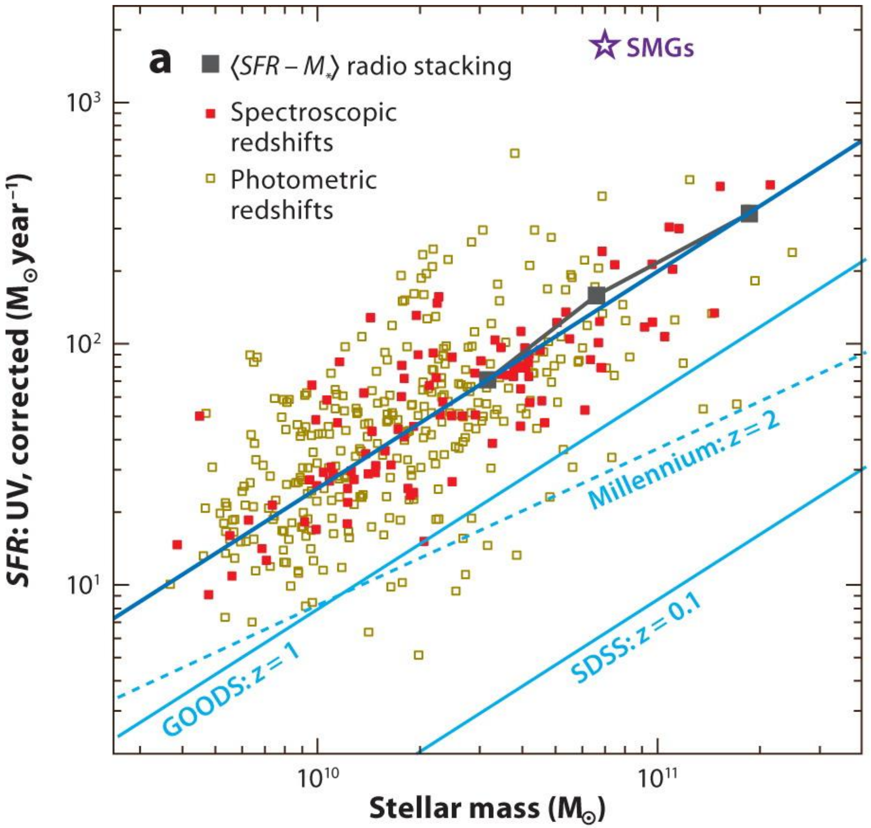
- Median extinction factor $(\mathrm{SFR}_{\mathrm{radio}}/\mathrm{SFR}_{\mathrm{optical}})$ 4.05 ± 0.30 ± (1.30)

Redshift Evolution



- SFR increases with redshift for 0.7 < z < 1.4. Consistent with earlier results, from DEEP2 and other samples.
  (e.g. Noeske et al. 2007, Dunne et al. 2009)
- High-redshift bins may be biased towards higher SFRs. Complete sample ($M_B < -20$) shows a less steeply increasing trend.

The Main Sequence

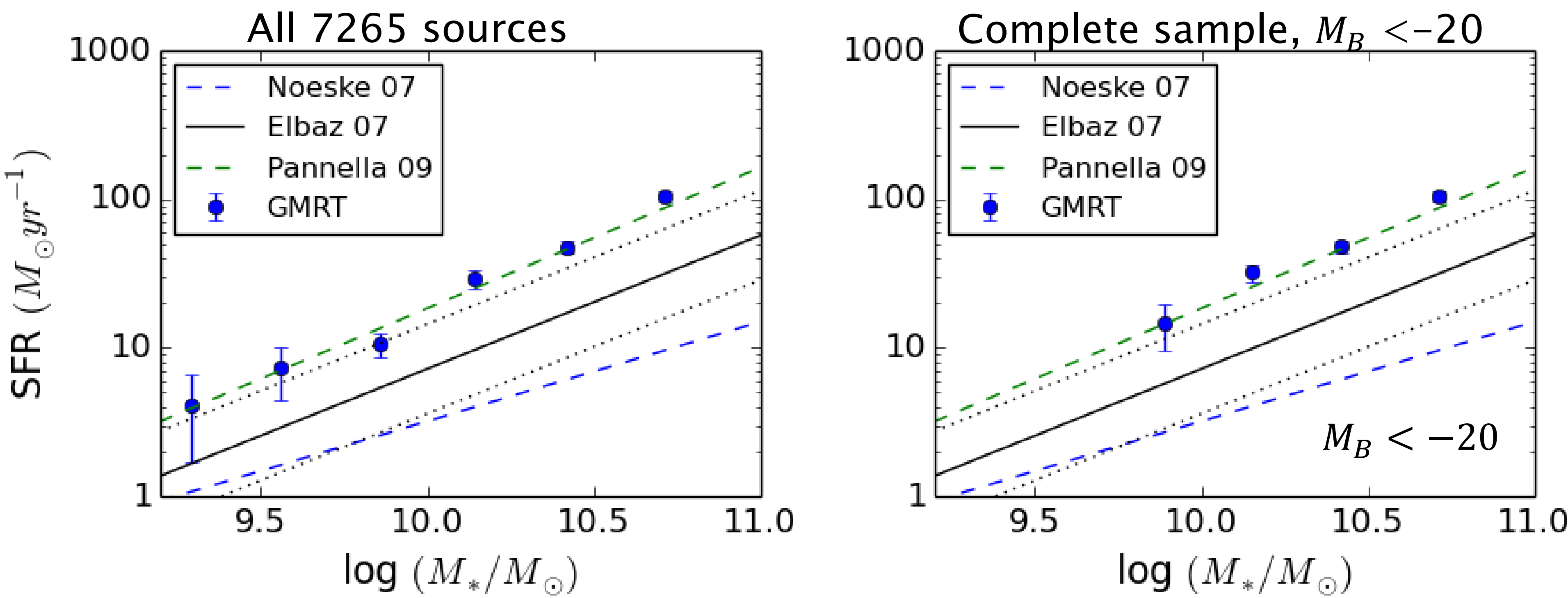


(Daddi et al. 2007)

- Normal disk galaxies lie on a “main sequence”, with the SFR increasing roughly linearly with the stellar mass. Star formation is much more efficient at higher redshifts, at a given stellar mass

(e.g. Brinchmann et al. 2004, Noeske et al. 2007, Daddi et al. 2007, Rodighiero et al. 2011)

The Main Sequence



- $SFR = (28.8 \pm 10.7) \times (M_*/10^{10} M_\odot)^{0.95 \pm 0.08} \quad (M_B < -20)$

- Consistent with SFR–M* relation at z~1 from mid-IR + UV studies.
  (Elbaz et al. 2007)
- Surprising agreement with radio SFR–M* relation in z~2 BzKs!
  (Pannella et al. 2009)

Summary

- Carried out a median-stacking of the radio continuum emission from 7265 star-forming galaxies at $z \sim 0.7 - 1.4$ in 4 DEEP2 fields.

- Clear detection of the stacked radio emission:

  Flux density = 8.42 ± 0.61 μJy (~14σ).

- FIR–radio correlation: Median SFR = 20.87 ± 1.53 (± 6.59) $M_{\odot}/yr$

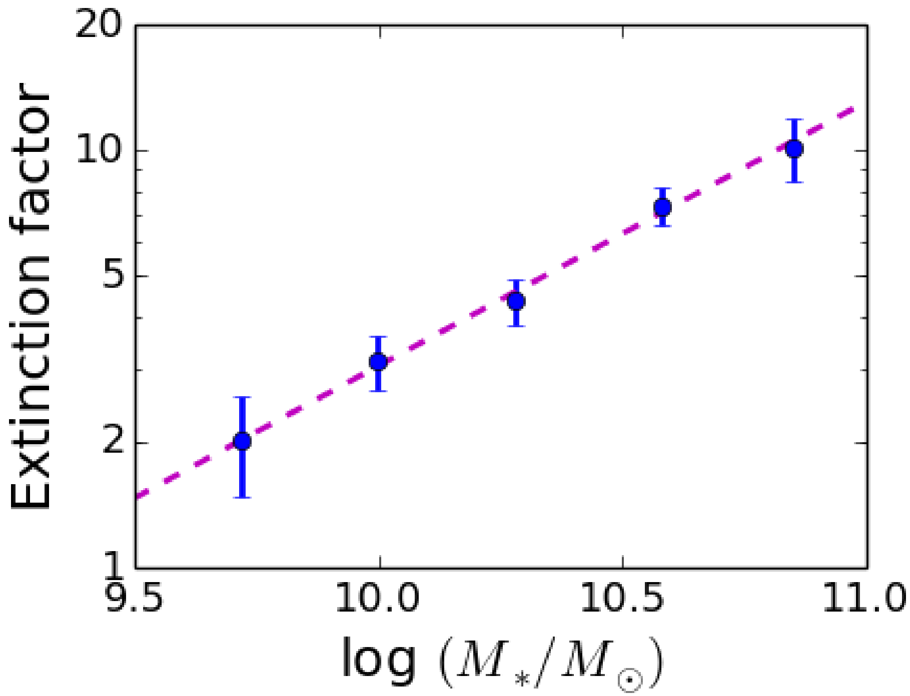
- The SFR appears to increase with redshift, over z ~ 0.7 – 1.4. Shallower redshift dependence for a complete sample.

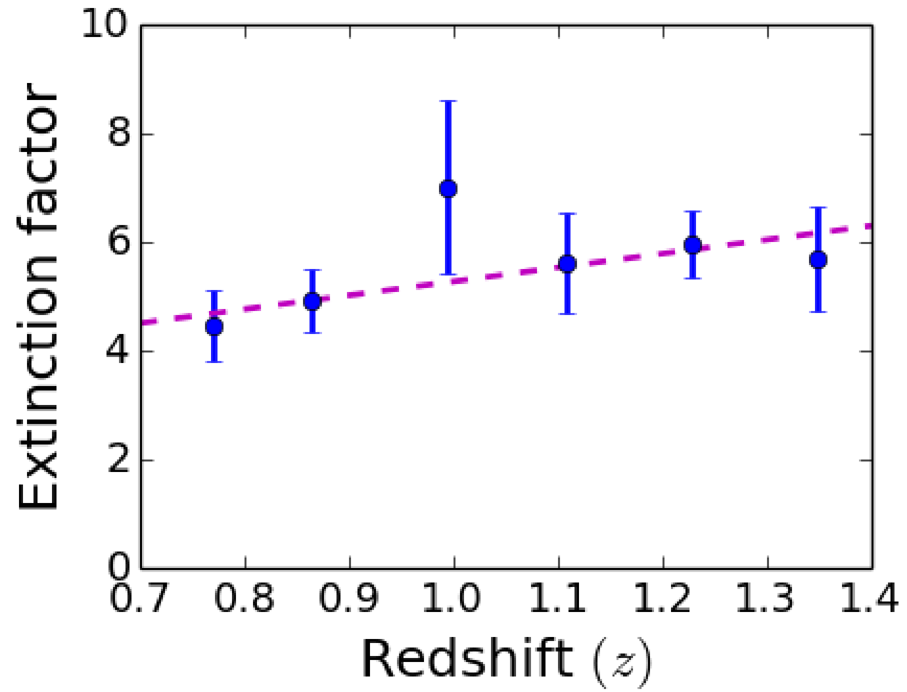
- Clear detection of the main sequence:

$$\mathrm{SFR} = (28.8 \pm 10.7) \times \left(M_{*}/10^{10} M_{\odot}\right)^{0.95 \pm 0.08}$$

- Surprising agreement with radio SFR–M* relation in z~2 BzKs!

Extinction factor





- Extinction factor (ϵ) strongly depends on M_* :

$$\epsilon = (6.1 \pm 1.0)\, logM_* - (57 \pm 10).$$

- Consistent with previous studies.

(Pannella et al. 2009, 2015, Oteo et al. 2014)

- Extinction appears to be independent of redshift.

SFR vs colour